LATTE – Linking Acoustic Tests and Tagging using statistical Estimation

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LONG-TERM GOALS

The goal of this project is to improve our ability to predict the behavioral response of beaked whales to mid-frequency active (MFA) sonar, by making better use of data already collected, or being collected as part of other projects.

OBJECTIVES

We aim to construct and fit mathematical models of beaked whales diving behavior, and their response to MFA sonar. These models will be parameterized by fitting them simultaneously to three sources of data: (1) short-term, high fidelity tagging studies on individual whales (some of which comes from animals exposed to acoustic stimuli); (2) medium-term satellite tagging studies of individual whales (some of which we hope will come from data collected during navy exercises); and (3) long-term passive acoustic monitoring from bottom-mounted hydrophones (much of which comes from data collected during navy exercises). All data will come from the Atlantic Undersea Test and Evaluation Center (AUTEC), Bahamas, and the surrounding area. Hence our models and predictions will be directly applicable to animals in that area, although we hope they will be of more general relevance.

Outputs of the model are designed to be compatible with risk evaluation and mitigation tools and models developed under other ONR initiatives, such as Effects of Sound on the Marine Environment (ESME) and Population Consequences of Acoustic Disturbance (PCADS). Hence, the model will:

(1) predict the behavioral responses of individual beaked whales to MFA sonar;

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(2) provide sufficient information to assess the level of “take” likely to result from sonar operations;

(3) provide sufficient information to allow the energetic costs of disturbance by MFA to be estimated; (4) provide a modeling framework within which information concerning behavioral responses of beaked whales can be interpreted.

APPROACH

The overall modeling framework we are adopting is called a “state-space model”. Such models describe the evolution of two stochastic time series in discrete time: (1) a set of true but unknown, states, which in our case are the positions of diving whales, and (2) a set of noisy observations related to these states, which in our case are the three sources of data described above. A “process model” describes how the states change through time, and a set of “observation models” describe how the observations link to the states. Here, the process model is a stochastic, discrete-time model for the movement of individual diving beaked whales, and their group dynamics.

The project is divided into four tasks, each divided into subtasks, as described in the project proposal.

- Task 1 involves specifying the process model; this is largely the responsibility of the main postdoctoral research fellow working on this project, Dr Tiago Marques, in collaboration with Thomas, Boyd and Harwood.
- Task 2 involves developing the formal fitting procedures required to fit the state-space model to the three sources of data. Computer-intensive Bayesian statistical methods will be used. Such methods have been the subject of enormous growth in research activity recently; nevertheless fitting complex movement models to data at such a range of temporal scales is very challenging, and considerable effort is being devoted to algorithm development. This is being undertaken by Marques and Thomas.
- Task 3 involves processing the data required as model inputs. A large amount of acoustic and tag data are potentially available, but much of it requires extraction and processing before it can be used. This is being undertaken by staff at NUWC, under the direction of Moretti.
- Task 4 involves project supervision and coordination. This includes monthly tele-conference progress meetings, as well as face-to-face meetings at least once a year, and is coordinated by project manager Catriona Harris at St Andrews.

WORK COMPLETED

The project started in April 2010. Tasks 3 (data processing) and 4 (project management) have been developing as expected. Data processing is ongoing and happens as required, and we provide specific details below. We continue to have regular tele-meetings to discuss progress, allowing us to keep LATTE on track. Since last year’s progress report, we were able to meet face-to-face 5 times, largely taking advantage of travel opportunities funded under other projects: Tampa (November), St Andrews (February), Washington (May and June), and Boston (July). In St Andrews and Boston we held LATTE dedicated meetings. This greatly facilitates coordination (task 4, note Catriona Harris has been replaced by Danielle Harris for the duration of her maternity leave). We have been coordinating with other projects as mentioned under “Related projects”, below.

LATTE is moving forward in two main fronts: (1) modeling whale movement in 3 dimensions (3D) using DTAG data, and combining this with acoustic localizations obtained from AUTEC's hydrophones, and (2) using the data from Submarine Commander Course (SCC) exercises to model the probability of disturbance in beaked whale behavior, using as a proxy for "normal" behavior the deep diving patterns observed in the absence of sonar use.

Regarding the modeling of whale movement, before LATTE, the procedure to obtain a 3D track involved a series of independent steps. This included the estimation of whale speed using a simple bivariate state space model and combining that with DTAG data (depth, heading, pitch, tag-on position) to obtain the 3D track. We have now developed an algorithm that integrates these steps into a single procedure, and fitted the model to data (Figure 1). A main advantage of this procedure is that it is simple to calculate precision measures associated with the resulting location estimates in 3D, which was not possible before. The next step is to refine the model currently used to resolve some of its idiosyncrasies. As an example, the current model assumes that heading and pitch are observed without error. This is inconsistent with the fact that the current model assumes that depth is observed with error. Including both angles as states in the model is the obvious way to move forward, but that will require different fitting tools. This work was presented at the International Statistical Ecology Conference (ISEC) in Norway (July 2012), and we are drafting a paper on the results.

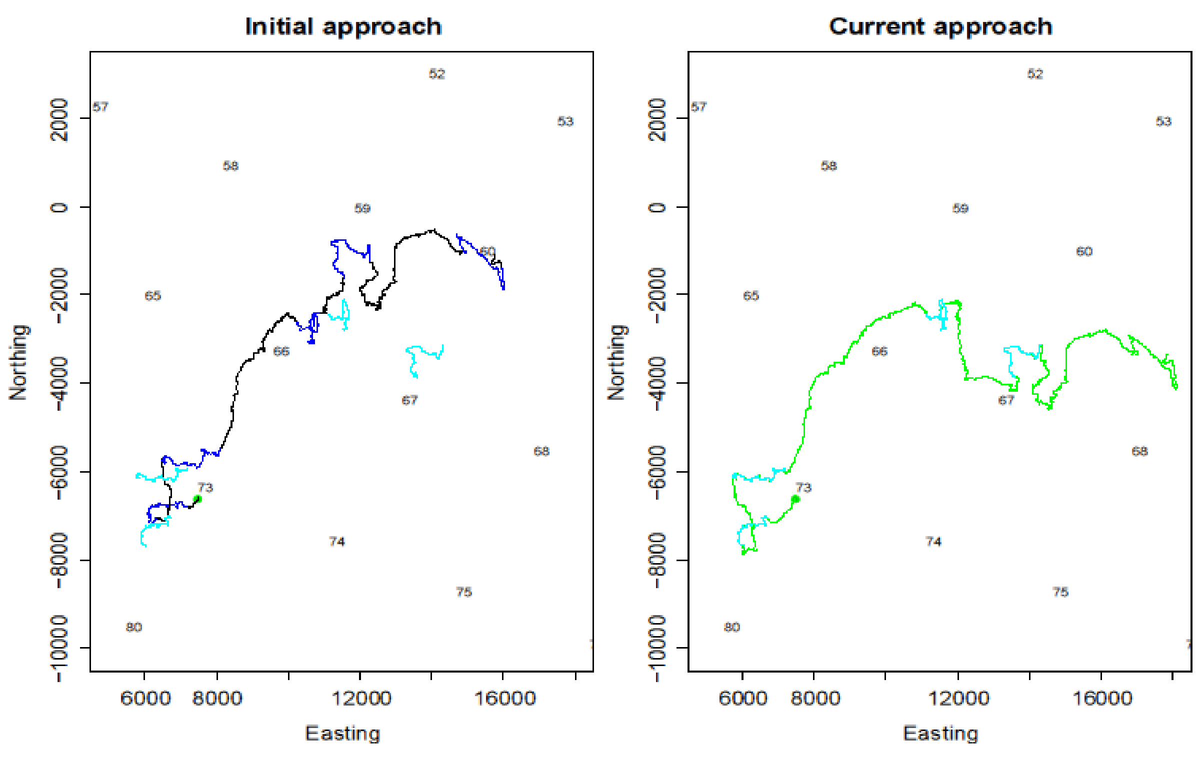

Figure 1 – Estimated whale tracks in 2 dimensions, based on DTAG data (heading, pitch and roll files). Light blue lines represent acoustic localizations using AUTEC's hydrophones. Left: a pseudotrack: track estimated without the independent data on acoustic localizations. Black and dark blue lines represent respectively the estimated track above and below 300 m depth. Right: a georeferenced track, integrating acoustic-based localizations from AUTEC in the model fitting procedure. Green line represents estimated track, with acoustic localizations superimposed in light blue. Improvement on the right plot is evident, as now the track follows closely the known locations.

The model considered above does not implicitly account for the possibility that the animal can be in different behavioral modes, each with different associated movement parameters. In parallel, we are pursuing a closely related topic, in which behavioral modes are used to model animal movement. We started by modeling depth alone (i.e., 1D), and will extend to 3D modeling next. Our models started by assuming that beaked whales can be in one of 4 behavioral modes: (1) at the surface, (2a) descending, (2b) foraging at depth and (2c) ascending. It soon became apparent that traditional models, like hidden Markov models (HMM), would not be enough. These have strong implications in the times an animal remains in each state, which would not hold here. So we have considered extensions to hidden semi Markov models (HSMM). It is also clear that transition between states has to be also dependent on the actual depth, which led us to consider feedback Hidden semi Markov models (FHSMM). Further, the model is currently being updated and improved, and at present state 1 includes 4 sub-phases: (1) at the surface, (2) shallow dive down, (3) shallow dive horizontal and (4) shallow dive up. In figure 2 a depth profile is compared to a simulated depth profile using parameters obtained from fitting the model to DTAG depth data. This is joint work with another CREEM research fellow, Dr. Roland Langrock, who's expertise on HMMs and extensions has been leveraged on this project.

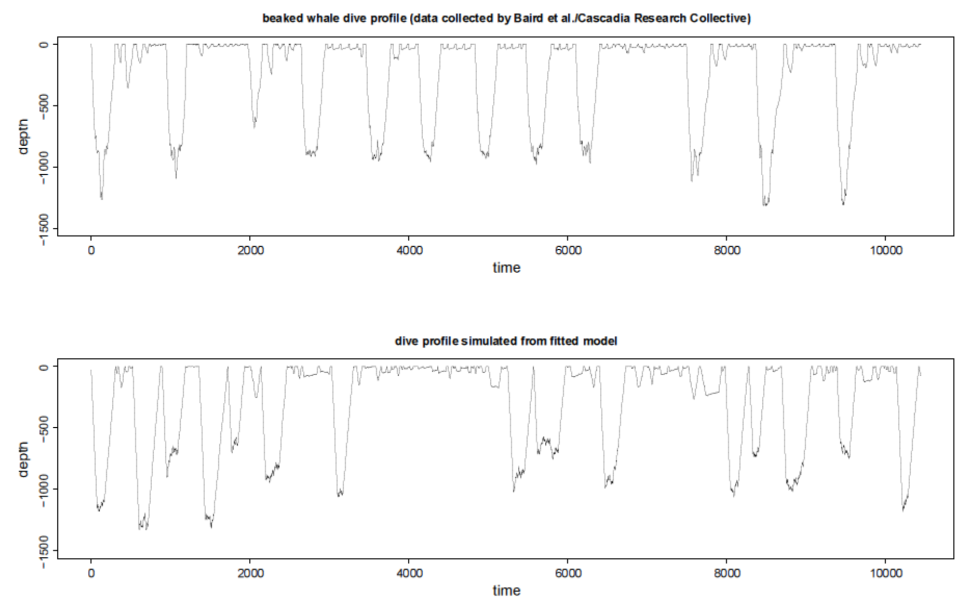

Figure 2 – Observed depth profile (top) and simulated depth profile (bottom). While some features are well captured in the simulated profile (e.g. depth distribution of deep dives), others (e.g. time at the surface) still require fine tuning.

Modeling of SCC data continues. We focus our efforts on a model that explains dive occurrence at hydrophones within 30 minute periods. This model allows the derivation of "dose-response" curves, representing the probability that behavior one might observe under the absence of a disturbance is disrupted as a function of a dose of disturbance, here measured as noise. To do so, our partners at the Navy Undersea Warfare Center (NUWC) run models taking as inputs the locations and levels of sound (mostly sonar) sources, and which outputs values of predicted noise at distances and depths throughout the AUTEC range. We then used these to model the probability of a deep dive occurring. Strictly, we model the probability of a deep dive occurring and being detected, but we assume that any deep foraging dive within the AUTEC range is detected, which given the system characteristics, is perfectly

reasonable. This work is being developed in close synergy with another project, PCADs (mentioned below). An example of a dose response curve modeled from this data is presented in figure 3.

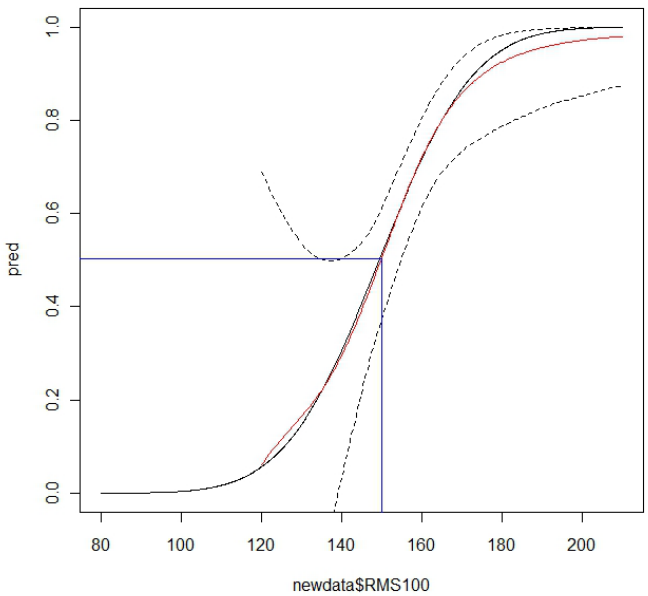

Figure 3. Probability of disturbance as a function of RMS level @ 100m (red), sigmoidal fit (blue), and the 97.5 and 2.5 quintiles (dotted). The 50% probability of disturbance as a function of RMS is indicated in blue.

When integrating data at several scales, we will need a hierarchical model that considers group movement, and then embedded within that a model to account for individual animal movement. While we have now developed models for individual movement, there is a critical lack of data allowing inferences and model development of animals within a group. A model based on a correlated random walk around a group center has been proposed, but due to lack of data from simultaneously tagged animals it does not seem simple to check how adequate is any such model we put forward. However, the acoustic footprint of a group, i.e., the data we routinely have access through AUTEC's hydrophones, might be extremely dependent on that behavior. We have started to look into using simultaneous localization of animals within a group using AUTEC's hydrophones to be able to understand better this fundamental link between data on individual movement and AUTEC range level data, which integrates individual and group movement.

RESULTS

We list below specific outputs related to each of the project components:

- We have now been able integrate what were before a number of independent steps into an integrated procedure that goes from DTAG data (and eventually acoustic detections) to a 3D whale track. An example is shown in figure 1, and this generated the following presentation:
- MARQUES, T. A., JOHNSON, M., SHAFFER, J., WHITE, C. & THOMAS, L. (2012) Using animal-borne tags to estimate whale tracks in 3-dimensional space using state space models.3rd International Statistical Ecology Conference. Sundvolden, Norway.

- We have developed a movement model using behavioural states fitted within a hidden Markov model framework, as presented in:
- LANGROCK, R. (2012): Extensions of hidden Markov models for animal telemetry data. 3rd International Statistical Ecology Conference. Sundvolden, Norway.
- MARQUES, T. A., LANGROCK, R. & THOMAS, L. (2012). Modeling beaked whale dive data using feedback hidden semi-Markov models. XXth Congress of the Portuguese Statistical Society, Porto, Portugal

We are currently drafting 3 papers, based on the work above, to submit to specialized journals, namely:

MARQUES, T. A., JOHNSON, M., SHAFFER, J. & THOMAS, L. (in prep). From DTAG data to whale tracks: estimating 3-dimensional tracks using state space models

MARQUES, T. A., LANGROCK, R. & THOMAS, L. (in prep). Modeling beaked whale dive data using feedback hidden semi-Markov models.

MORETTI, D., SHAEFFER, J., MCCARTHY, E., MARQUES, T. A., THOMAS, L.(in prep) . Modelling probability of disturbing diving behaviour as a function of noise.

IMPACT/APPLICATIONS

Determining and mitigating the effect of mid-frequency active sonar on marine mammals is a key goal for the US Navy in complying with marine mammal protection requirements. The proposed research is aimed at developing tools to facilitate this. Although current behavioral response experiments provide key information, it seems unlikely that they will ever yield large enough samples to provide a complete picture of the response of vulnerable species to sonar. By combining information from these rare, directed studies with the large amount of opportunistic data available from exercises on instrumented testing ranges, obtaining the required information about animal response becomes feasible. This information could possibly be used to avoid future mass strandings, and can certainly be used to better estimate the number of animals exposed to high levels of sound (likely fewer than currently assumed).

RELATED PROJECTS

LATTE is part of a larger network of projects funder under a variety of Navy related sources whit the overall goal of better understanding cetacean movement and behavior and relating this to potential impacts from the use of sonar and other anthropogenic impacts. Below we list a number of related projects which LATTE's PI's are involved with which provide inputs to LATTE or which are natural costumers for LATTE's outputs:

1. Behavioral Response Study – an experimental approach to determining the behavioral response of marine mammal species to MFA sonar that provided the motivation for, and much of the data for, the current study (http://www.nmfs.noaa.gov/pr/acoustics/behavior.htm)

2. M3R program[1] – the passive acoustics monitoring algorithms and tools development program at NUWC that has facilitated much of the data processing work used in the current project.
3. DECAF[1] – a project developing methods for density estimation from fixed acoustic sensors that provided the initial monitoring tools being further developed in this project (http://www.creem.st-and.ac.uk/decaf/).
4. PCAD – a project to implement the population consequences of acoustic disturbance model to four case study species including beaked whales at AUTEC. Output from the LATTE project will provide useful input into PCAD-type models, even if the outputs come too late for direct use in the current PCAD project.
5. The way they move[1] – a research project at the University of St Andrews developing algorithms for fitting state-space models to terrestrial animal tag data; the current project is leveraging many of the findings from this project.
6. Cheap DECAF – a continuation of the work developed under DECAF, now aimed at estimating density from acoustic data using scarce resources (e.g. single sensors)
7. MOCHA – develop and implement innovative methods for the analysis of cetacean behavioral response studies (http://www.creem.st-and.ac.uk/mocha/)

[1] These projects have now officially finished, but ongoing research from these is closely related with the research developed under LATTE.